HYDRODYNAMIC SLUG SIZE IN MULTIPHASE FLOWLINES

Abstract

Hydrodynamic slugs are understood to be initiated by the instability of waves on the gas-liquid interface in stratified flow under certain flowing conditions. When hydrodynamic slugs are numerous, the pipeline is said to be operating in the slug flow regime. The slug flow regime is characterised by complex gas-liquid flows often exhibiting chaotic behaviour.

Commercially available one-dimensional transient flow simulators rely on correlations to model the complex three-dimensional multiphase phenomena within a slug. These correlations can be tuned to field data giving good *a posteriori* predictions for operating facilities. However, their ability to make *a priori* predictions of slug flow (including slug size and frequency) remains limited. Hence, good design practice still requires the application of healthy design margins.

This note considers the subject of hydrodynamic slugging and qualitatively addresses the accuracy of the prediction methods.

Introduction

In many oil and gas developments incorporating multiphase flowlines, multiphase surges are a major Flow Assurance concern due to the excessive demands large changes in oil and gas flow rates place upon the processing facilities. Multiphase surges come in three forms:

1. *Hydrodynamic Slugs*: A property of the stratified flow regime where slugs are formed due to instability of waves at certain flow rates.
2. *Terrain Induced Slugs*: Caused by accumulation and periodic purging of liquid in dips along the flowline, particularly at low flow rates.
3. *Operationally Induced Surges*: Created by forcing the system from one steady state to another. For example, during ramp-up or pigging operations.

As these three forms of surges are quite different, they require different analytical techniques. This note focuses on hydrodynamic surges, and their prediction.

Slug Formation

Figures 1 to 3 show a series of slides from an animation of slug formation available on the Feesa website.

The illustration is presented in a Lagrangian perspective, following the slug along the pipeline. Initially the flow is stratified (Figure 1), i.e. the gas is at the top of the pipe and the liquid is at the bottom.

As gas passes over a wave there is a pressure drop, then a pressure recovery creating a small force upward within the wave, analogous to the Bernoulli effect when gas flows over an aerofoil. Under the correct conditions, this force is sufficient to lift the wave until it reaches the top of the pipe. This sudden growth in wave size due to gas flow is triggered by the Kelvin-Helmholtz instability.

Figure 1 Kelvin-Helmholtz Wave Growth

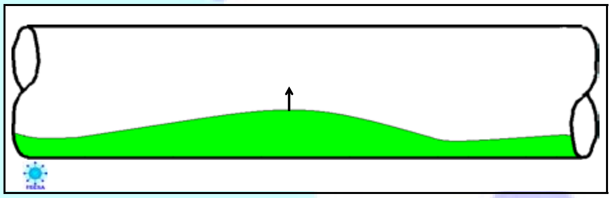


Figure 2 Slug Nose Ingress and Tail Shedding

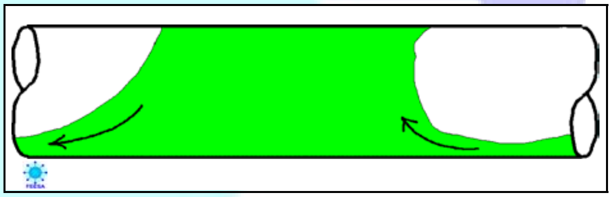
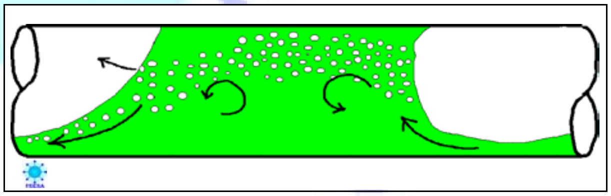


Figure 3 Gas Entrainment



Once the wave reaches the top of the pipe, it forms into the familiar slug shape (Figure 2), with a *nose* (right hand side) and a *tail* (left hand side). The slug is pushed by the gas and so travels at a greater velocity than the liquid film. Because of this there is ingress of liquid into the slug nose.

In a Lagrangian frame, the ingress of liquid into the front of the slug forms a *jet* which entrains gas bubbles, as shown in Figure 3. This gas entrainment serves to reduce the average liquid holdup in the slug, interfere with the mechanism of liquid ingress and increase the turbulence within the slug.

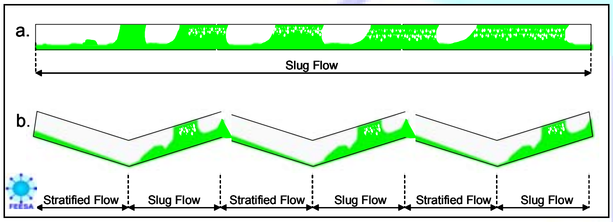
Slug Growth

As liquid enters the slug through the front, it also drains under gravity through the tail. The difference in rates determines the rate at which the slug grows or decays and ultimately determines the size of the slug.

The rates of liquid ingress and shedding, and the turbulence within the slug, determine whether the slug will persist or not. These depend on the local flowing conditions, fluid physical properties and pipeline inclination. In particular, the evolution of slugs is very sensitive to the pipe inclination and changing the inclination by less than a degree can be sufficient to tip the balance causing a flow regime transition. Thus, peaks and troughs along the pipeline profile of relatively small amplitude (for example less than a pipe diameter) can have a very significant effect.

The possible effect of incorrectly specifying the flowline undulations is illustrated in Figure 4 where the flow regimes of a simple horizontal topography (Figure 4a) and a topography with some undulations (Figure 4b) are compared. The multiphase flow in Figure 4b switches between the stratified and slug flow regimes, implying that not only could the slug sizes differ markedly but the pressure drops could be very different also. Few pipelines (if any) have constant inclinations, most undulate following the natural terrain. Therefore, when modelling multiphase flow, it is important to represent these undulations as faithfully as possible.

Figure 4 The Effect of Pipeline Inclination



A significant proportion of the frictional pressure drop in multiphase flow is thought to be due to the turbulent region within the slug. Thus the size of the turbulent region can have a significant effect on the frictional pressure losses in a pipeline.

As discussed earlier, an added complication is the effect of the gas bubbles within the slug that can be entrained by the liquid ingress into the nose. This entrainment affects the speed of the slug, the growth rate and the turbulence, and hence the frictional pressure drop of the slug.

A slug is therefore a complex three-dimensional turbulent multiphase phenomenon making it very difficult (arguably impossible) to model exactly.

Slug Interaction

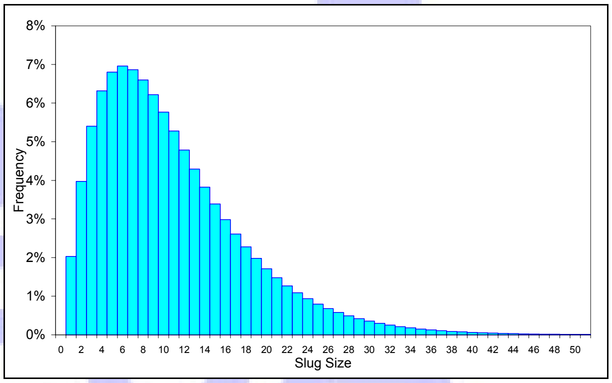
The fact that there are multiple slugs in the pipeline introduces a further complication. Large flowline systems may have many tens of slugs, generated at different locations, at different times and travelling at different velocities. These slugs interact with each other either directly or indirectly, meaning that individual slugs cannot usually be considered in isolation.

A flowline operating in the slug flow regime, often behaves like a chaotic system exhibiting sensitivity to the initial conditions. This suggests that in order to predict the exact behaviour of a slugging flowline, one must define the initial and boundary conditions perfectly. However, this being said, it is usually not necessary to predict the behaviour exactly. Fortunately, observations indicate that slugging pipelines often obey chaotic attractors and do not normally follow wild excursions in state space. In design, one is usually interested in the extent of the attractor (e.g. the maximum holdup in the slug catcher). Therefore, simulating an adequate number of cycles, and sampling with a Poincaré section should be sufficient to establish the picture for design.

Slug Size Distribution

The rich complexity of slug flow combines to produce a range of slug sizes from a given flowline under given conditions. Hence slug size data is often expressed in frequency-size distribution plots. Such a distribution is sketched in Figure 5. The plot shows that while the mean slug size may be comparatively small, there are less frequent slugs that are many times larger.

Figure 5 Typical Slug Size Distribution



Slug Size Prediction

There are two main methods that are typically used for slug size prediction:

1. Simple correlations of field data

2. Transient 1D slug-tracking simulation

Both methods are heavily reliant on good correlations of field and/or laboratory data, either directly in the case of the former, or in terms of a closure relationship for the latter. However there is a limited amount of slug flow data with sufficient detail to correlate phenomena such as tail shedding, gas entrainment, slug interaction, the effect of three phases and the various other important three-dimensional multiphase issues mentioned above.

The available transient slug-tracking simulators use empirical correlations to compensate for the fact that their one-dimensional models cannot model these mechanisms directly. It is unlikely that these correlations are particularly accurate and unfortunately the inherent errors can have a compound effect on the ultimate slug size. For example, an error in calculating the balance between liquid inflow and outflow through a slug of a few percent, could mean an error in the eventual surge of several cubic metres per slug. This has obvious ramifications for the design and operation of slug catchers.

Feedback from operators suggests that slug sizing using transient slug-tracking simulation is less than perfect. Such simulations do, however, give reasonable predictions when they have been tuned to field data. This makes their application as online real time simulators of particular value. However, the engineer charged with designing a new flowline and slug catcher system does not this have the benefit of field data and must use the tool in a wholly predictive manner.

The simpler (often statistical) correlation methods, are developed by correlating field slugging results to key parameters such as flowline diameter and fluid physical properties. However, these methods ignore the important effect of topography, and can therefore give misleading results. For example, these methods can predict slug lengths longer than the flowline! Nonetheless, these correlations have been used on numerous oil developments and in the absence of reliable transient predicts do provide another string to the engineer's bow.

Slug modelling using the available methods is stretched even further for large diameter flowlines and risers. For not only should the correlations themselves be called into question, but the very mechanisms on which they are based may also be incorrect. For example, there is evidence to suggest that conventional slug flow does not occur in large diameter vertical pipes and that other less coherent flow regimes may prevail.

Finally, the advances in Computational Fluid Dynamics (CFD) and the extension to multiphase flows needs mention since this perhaps offers a long-term solution to multi-dimensional multiphase flows. Many workers have shown how the fundamental equations of fluid mechanics can be averaged and discretised in three-dimensions for multiphase flows and have produced successful solutions to engineering problems. However, as with all of the methods described, the ultimate accuracy depends intrinsically on the empirical relationships that are used to close the model, and this is where these advanced methods need additional improvement. Furthermore, for the specific problem of multiphase flows in risers, which have large length to diameter ratios, it is difficult to see how the application of CFD could yield practical engineering solutions without very substantial improvements in computing power.

Slugcatcher Sizing

Slugcatchers should be sized to dampen surges to a level that can be handled by downstream processing equipment. Before dynamic models of the topsides facilities are available, the level of acceptable surging is unknown and designers are often forced to make assumptions vis-à-vis surge volumes, such as designing for the 'one in a thousand' slug.

However, knowing that the reliability of the prediction methods is questionable and that there is always a statistical chance of a larger slug (see Figure 5), the possibility of a slug arriving which is greater than the design surge volume cannot be completely discounted. Fortunately, there is often sufficient flexibility in the downstream process equipment to deal with an oversized slug, but even if it does cause a trip this may be acceptable provided that it is infrequent.

Conclusions

The modelling of hydrodynamic slug flow is in its infancy and though transient simulation is useful in calculating the effects of a known slug size they are still less than perfect at slug size prediction. Therefore, slug sizing results should always be treated with caution and slugcatchers should be designed with an ample design margin.

It is well-known that the potential lost production arising due to an under-designed slug catcher can be quite significant. And since the slug catcher usually represents only a small fraction of the overall development CAPEX, it is clear therefore that current best design practice should err on the side of caution.